GROUND TEST PERFORMANCE VALIDATION OF THE ARMY LEAP KILL VEHICLE

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Abstract:

The ground test plan for the Army LEAP kinetic Kill Vehicle (KV) is structured to validate all major subsystem performance prior to space flight missions. A carefully planned combination of lab, airbearing, strapdown and hover testing leads to a thorough and cost effective understanding of critical vehicle performance metrics. Simulation validation performed after each test enhances confidence for the subsequent tests with hover test data ultimately validating all aspects of vehicle performance before space flight testing.

I. Army LEAP Background and Objectives

The Army/Hughes Lightweight Exo-Atmospheric Projectile (LEAP) program is sponsored by Ballistic Missile Defense Organization (BMDO) and managed by the Army Space and Strategic Defense Command to develop and test extremely lightweight kinetic kill vehicle technology. At 13.5 lbs fully loaded, the Army/Hughes vehicle is the smallest exo-atmospheric kill vehicle currently built and easily fits into a number of existing tactical missiles for possible ballistic missile defense applications.

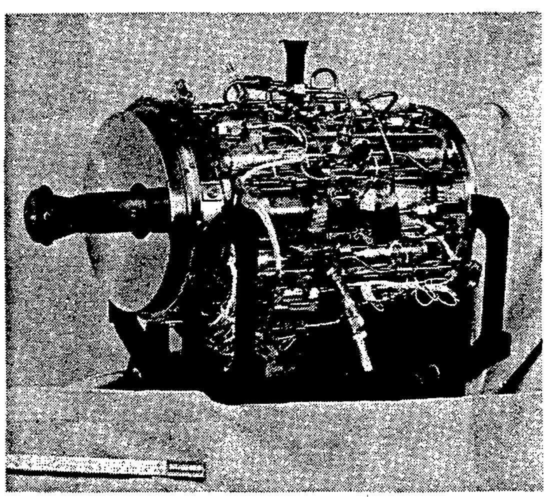

Figure 1: LEAP Kinetic Kill Vehicle

The LEAP KKV features a large aperture 128 x 128 medium wave infrared (MWIR) staring focal plane seeker mounted in a body fixed configuration on the KV front structural bulkhead. All vehicle electronics are completely integrated onto a single high density multilayer interface (HDMI) card mounted just behind the primary mirror of the IR seeker. An Inertial Measurement Unit (IMU) on the rear bulkhead provides accurate inertial reference updates for high accuracy hit-to-kill guidance performance at high closing velocities. Maneuver and attitude control are performed by the propulsion system which also forms the structural center of the vehicle. The propulsion features cruciform hypergolic divert thrusters and eight extremely high speed warm gas attitude control thrusters. Propellants are expelled from four cylindrical axially oriented tanks by pistons moving in opposing directions, two from each direction, to minimize center of gravity movement.

The guidance subsystem consists of the seeker, IMU, and the electronics unit used to process sensor and IMU information. The seeker utilizes cassegrain optics projecting an infrared image onto a 128 x 128 HgCdTe staring focal plane array operating in the medium wave band. Low level image processing is done by a number of custom LSI chips. Vehicle electronics are completely self contained on one double sided 5.6 inch diameter HDMI card located immediately behind the seeker's primary mirror. This electronics board hosts an Intel 80386 microprocessor based system operating at 20 MHz allowing guidance and attitude control operation at 60 and 360 Hz respectively. Inertial measurements are supplied by a pair of Marconi Electronics Systems Corp. multisensors mounted as an IMU on the rear propulsion bulkhead.

The propulsion unit is a bipropellant hydrazine-nitrogen tetroxide based liquid hypergolic system. Attitude control thrusters use warm gas generated by decomposition of the hydrazine through a catalyst bed. Valve

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response times in the millisecond range guarantee an extremely fast attitude control response time that assures minimal target smearing in the field of view during terminal guidance.

Propulsion pressurization is regulated by a feedback control system using a pressure sensor and computer controlled valve controlling the flow of high pressure helium supplied in three tanks mounted behind the front bulkhead. Fuel and oxidizer are drained from the four cylindrical propellant tanks in opposing directions maintaining knowledge of center of gravity motion to a fraction of a millimeter.

Fully fueled, the complete KV is capable of sustaining hover flight in excess of 25 seconds or of steering out several kilometers of initial error in a space flight intercept.

II. LEAP Ground Test Strategy

Ground test strategy for the Army/Hughes LEAP was developed early in the program and modified continuously to optimize confidence in system performance while minimizing cost and schedule impact to the program as a whole. In addition to complete system characterization and functional tests, six major subsystem tests were devised to develop complete confidence in KV performance prior to space flight testing.

Summary of Major Subsystem Tests

1) Probability of False Alarm: An integrated guidance unit is set up to stare at a simulated space background for extended periods. Seeker output is monitored to assure that no "targets" are acquired. This test is performed on every KV.

2) Motion Isolation: Angular oscillations representing normal attitude control performance are induced on a fully integrated kill vehicle while it is tracking a target. Guidance commands are monitored to assure that body rotations do not affect them.

3) Air Bearing: The guidance unit is integrated with a cold gas propulsion system, simulating actual propulsion performance. Closed loop attitude control performance is monitored for proper operation while tracking a collimated target source.

4) Development Test Projectile (DTP) Propulsion Firing: A partially integrated propulsion system is bench fired to verify critical propulsion subsystem performance values.

5) Strapdown Test: A fully integrated KV is bench fired while tracking a target to verify proper guidance unit performance in an environment induced by propulsion firing.

6) Hover Test: A fully integrated KV undergoes free flight hover in a netted enclosure while tracking a distant point source target.

A top level matrix has been developed to illustrate the key performance attributes validated by each of the tests. This matrix is given in Figure 2.

Confidence Rating
Medium
High
Complete

	Prob. False Alarm	Motion Isolation	Air-Bearing	Propulsion Firing	Strapdown	Hover
Acquisition	High	Complete				
Track		Medium	High			Complete
Attitude Control		Medium	High			Complete
Guidance		Medium			High	Complete
CG Control				Medium	High	Complete
Pressure Control				Medium	Complete	Complete
Propulsion				High	Complete	Complete

Figure 2. Top Level LEAP System Test Matrix

Each test demonstrates key attributes of performance while supplying data for other attributes which must be demonstrated on future tests. By hover test completion, subsystem performances have been completely demonstrated leading to complete confidence in space flight intercept performance.

The test plan is also designed to verify subsystem performances before they are needed in high cost tests such as strapdown or hover. Figure 3 shows how key subsystem performances were verified before commiting the KKV to hover or strapdown tests.

KV Critical Subsystems Testing	Air-Bearing	Propulsion Firing	Strapdown	Hover
Acquisition			verified	must work
Track	must work		verified	must work
Attitude Control	must work			must work
Guidance			verified	must work
CG Control		verified	verified	must work
Pressure Control		must work	must work	must work
Propulsion		must work	must work	must work

Figure 3. Critical Areas Are Tested Before the KKV is Committed to Hover Test

Every system parameter is tested at least once before an expensive test such as strapdown or hover. In the case of the air-bearing test, proper function of track and attitude control are required for success, but if the subsystems do not function properly, the test is easily repeatable by making algorithm modifications and retesting. This approach greatly reduces the risk associated with test success for the relatively moderate cost of having the hardware and software algorithms ready at least one test before they would otherwise be required.

Software Test / Simulation Validation

In parallel with the test program, the performance of the system is predicted by a number of kinematic simulation tools allowing continuous feedback to the engineer for design changes in response to changes in mission, scope and hardware performance. A network of simulation tools have been developed to streamline algorithm development and performance prediction. The nominal flow of simulation model and algorithm development is shown in Figure 4.

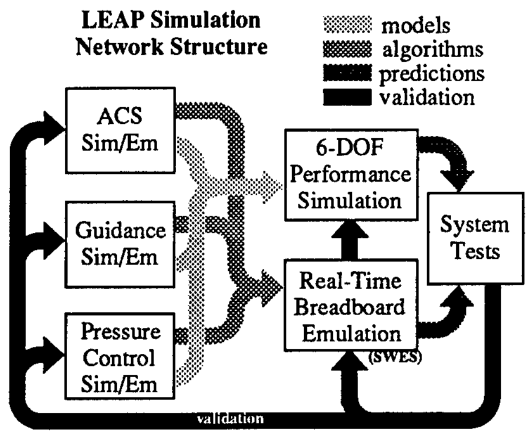

Figure 4. Multiple Simulation Tools are Utilized to Minimize Algorithm Development Costs and Maximize Performance Accuracy

Individual subsystem algorithm development times are improved by utilizing specialized simulation tools for that particular subsystem. The time to a finished software algorithm is reduced by actually developing the algorithms in the "C" computer language and transferring them directly to real-time software emulation.

The SoftWare Engineering Station (SWES) is a real time, closed loop software tool which uses a printed circuit board implementation of the kill vehicle electronics to duplicate its operating characteristics. Vehicle kinematics and sensor models are implemented with a 486 based PC and interfaced with the software/KV electronics with A/D and D/A converters. A. block diagram of the SWES is shown in Figure 5.

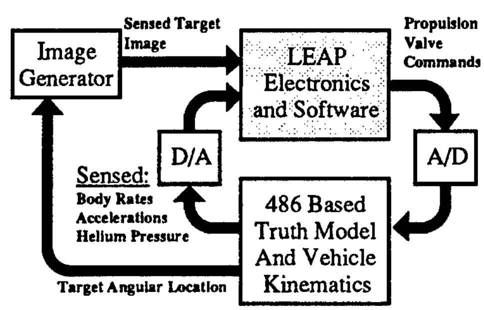

Figure 5. LEAP Real-time Emulator (SWES)

This configuration can be adapted to hardware in the loop (HWIL) testing such as air-bearing testing simply by sending thruster commands to the cold gas thrusters and substituting actual gyro and seeker output for the simulated values. Other HWIL configurations are easy to implement because the test designer can select

any combination of sensors as the test warrants. This real-time software exercise is more than a software evaluation tool, it is a partial hardware in the loop simulation which generates performance statistics in real time.

III. Airbearing and DTP Testing

The airbearing test replaces the standard three axis flight table hardware-in-the-loop simulation usually done for atmospheric missiles. The guidance unit is mounted on a vehicle which has three axes of rotational freedom but no translational freedom. The unit is supported on a sphere which is in turn floated in a socket using pressurized nitrogen. Rotational friction in this setup is extremely low. The air bearing configuration is represented in Figure 6.

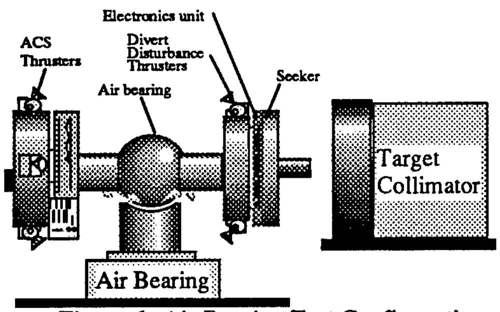

Figure 6. Air Bearing Test Configuration

Mass balancing is carefully done to reduce torque effects of gravitational force to zero. Attitude control torques and divert engine disturbance torques are simulated using cold gas thrusters which produce response times and angular accelerations similar to those produced by the actual propulsion system. A photograph of a Kill Vehicle test on the air bearing is shown below in Figure 7.

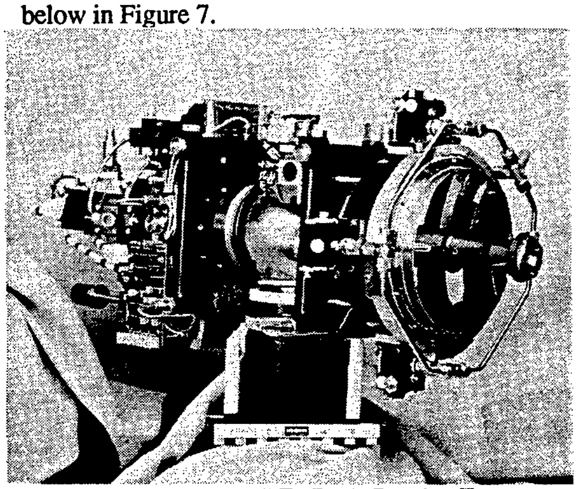

Figure 7. Integrated LEAP Air Bearing Test

The airbearing test was the first hardware in the loop test of the attitude control system with the tracker. While the target was moved by a swing arm, aimpoint inputs from the KV tracker were used by the ACS to keep the target near the center of the FOV. Disturbance torques were added by firing the divert disturbance thrusters to verify performance of the system with disturbance torques expected in flight.

The results were correlated to the simulation and modifications were made to the simulation to reproduce the amplitude and frequency of the ACS limit cycle. The precise noise history of a specific run from the IMU cannot be reproduced in the simulation, so the match in amplitude and frequency results was made statistically. Figure 8 shows close correlation between air bearing measurements and the simulation results.

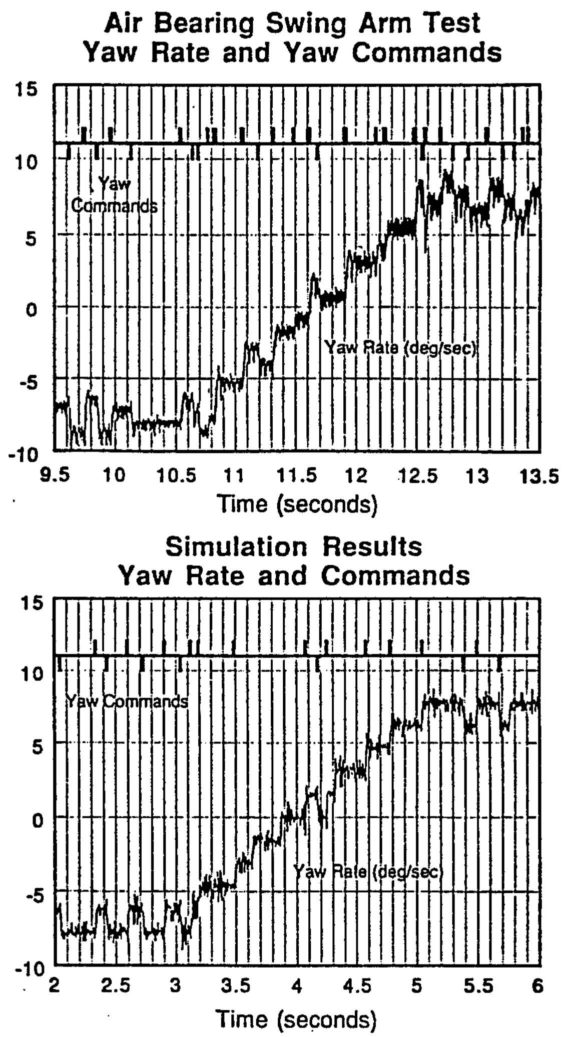

Figure 8. Simulation Body Rate Matching for Air Bearing test

The guidance algorithm was tested open loop by examining the guidance acceleration command while the body is undergoing the rate limit cycle of the ACS. This test is similar in nature to the motion isolation test but more accurately reproduces the angular motion expected in flight. Since the target projected by the collimator is stationary, guidance commands should be zero within the tolerances generated by simulation. Air bearing test results are used to confirm proper guidance operation in this open loop configuration.

The Development Test Projectile (DTP) test was a bench test of a partially integrated prototype propulsion system. The DTP was essentially one half of a propulsion system with two divert thrusters, two propellant tanks and 4 ACS thrusters. In a hard mounted bench test, it burned the nominal hover test and a typical space flight test duty cycle in sequence.

This test proved that the integrated propulsion system was capable of firing long sequences of divert pulses reliably without any thruster dropouts. A high duty cycle demand sequence on the ACS thrusters did not produce even a single thruster dropout, indicating a high level of valve reliability. In all subsequent system testing up to and including the space flight test, no thruster dropouts have ever been recorded.

At the end of the test, propellants are drained out of the fuel and oxidizer tank to determine uniformity of expulsion. In order to minimize CG motion during flight, the LEAP propulsion system relies upon piston driven counter-draining propellant tanks. Data from this test confirmed that the CG motion would only be a fraction of its 2 mm requirement. Later data from the strapdown and hover tests confirmed these results.

IV. Strapdown Test

The first fully integrated LEAP kill vehicle, called the Ground Test Projectile (GTP) was first tested in a strapdown configuration and later in an actual hover flight test. The strapdown test fired divert and ACS thrusters in a preprogrammed manner while the guidance system tracked and determined guidance commands for open loop evaluation. It was the first test which used the integrated Hughes electronics to drive the Marquardt propulsion system. A photograph of the strapdown test is shown in Figure 9.

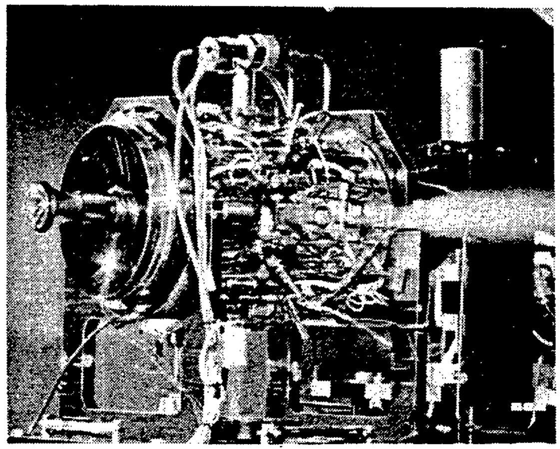

Figure 9. LEAP GTP During Strapdown Test

The GTP was "soft" mounted to a bench during the test which prevented any large translational or angular motion but allowed enough compliance to preserve most of the body bending modes. The vehicle was instrumented for structural dynamics and temperatures, providing valuable data on the environment to be experienced by the projectile during flight

Tracker and IMU functions were carefully monitored during the strapdown test to ensure the vibration environment would not significantly degrade performance of these key elements which are critical for the hover test. Both tracker and IMU performed flawlessly. Data reduction showed that seeker noise statistics were effectively unchanged by the propulsion firing and IMU vibration induced drift was within requirements.

The propulsion pressure control system was used closed loop for the first time during this test and performed perfectly. Propellant tank pressures were held within tolerance even at the beginning of the flight where the free volume behind the pistons was very small.

The propulsion manifolds of one ACS thruster and one divert thruster were instrumented for pressure in order to determine actual thrust values. The high pressure helium tanks were also instrumented to determine the blowdown characteristics of the helium tanks as their pressure was bled into the propellant tanks. Data gathered from these tests permitted simulation modeling adjustments and improved kinematic performance predictions for the space flight tests.

V. Hover Test

The successful completion of a hover test requires all kill vehicle subsystems to operate properly. It is the most comprehensive end-to-end test of an exoatmospheric kill vehicle short of an actual space flight intercept. The kill vehicle proves its ability to fly and guide, controlling both lateral accelerations and attitude motion while tracking the target. The Army/Hughes LEAP hover test added an extra step by using the terminal guidance algorithm for closed loop guidance during the flight. Therefore, terminal guidance was also demonstrated in this hover test.

The vehicle lifted off its cradle and flew for a total of seven seconds while tracking the target without a single dropout from beginning to end. Altitude was held to within 15 cm of the objective and total axial drift during the flight matched the predicted value of approximate 0.9 m rearwards. Figure 10 is a photograph of the kill vehicle during the hover test. Figure 11 compares predicted to actual vehicle altitude during hover.

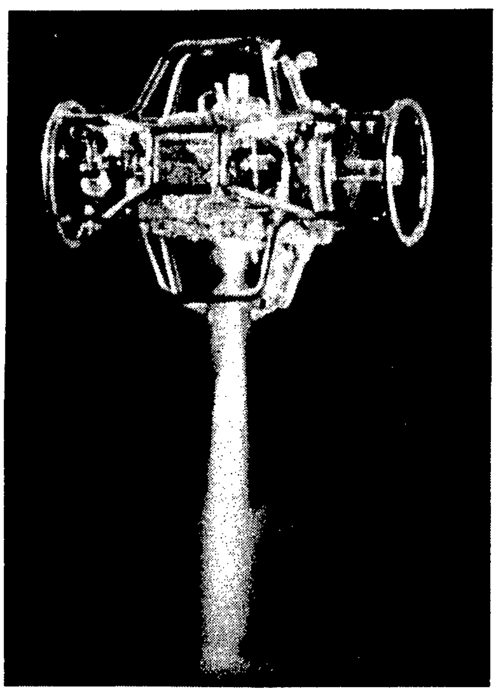

Figure 10. LEAP Kill Vehicle in Hover Flight

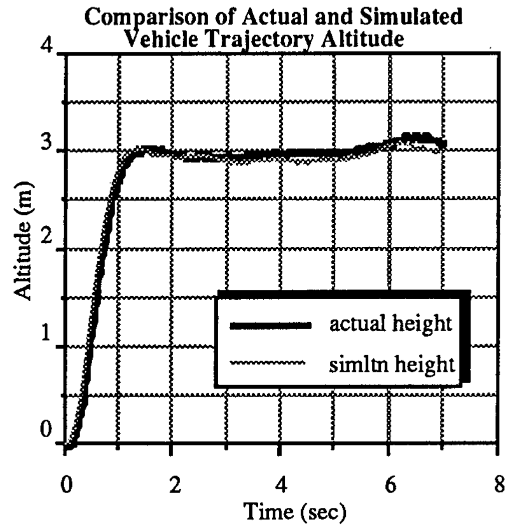

Figure 11. Altitude vs. Time Trajectory Matching for the LEAP Hover Test

All of the major software functions which would run closed loop in a space intercept did so in this hover test. The attitude control, pressure control, and guidance all ran as they would in an actual intercept. As with the strapdown test before it, all subsystems performed flawlessly and simulation results matching trajectory data.

VI. Summary:

Careful planning of the LEAP ground test sequence permitted all major KKV performance parameters to be proven. Careful open loop pre-testing of major subsystems allowed subsystem performance validation prior to critical closed loop testing. Development of a real-time software test station allowed quick and accurate software testing and flexibility in hardware-in-the-loop test planning.

Each ground test validated key areas of subsystem performance so that all critical paths were tested before the hover test. This was vital because the hover test demanded performance from every subsystem for success. The hover test validated closed loop performance of all major subsystems including terminal guidance.

The Army/Hughes LEAP ground test program reliably validated system performance and culminated in a successful free flight hover test. The successful completion of this ground test program paved the way for high-confidence space flight tests and future ground and space testing of advanced technology versions of the Army/Hughes kill vehicle.